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AUTOMATED DELAY MEASUREMENT SYSTEM FOR AN EARTH STATION FOR TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER

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Abstract

The measurement of the difference of the transmit and receive delays of the signals in a Two-Way Satellite Time and Frrequency Transfer (TWSTFT) earth station is crucial for its nanosecond time transfer capability. Also, the monitoring of the change of this delay difference with time, temperature, humidity, or barometric pressure is important for improving the TWSTFT capabilities.

An automated system for this purpose has been developed from the initial design at NMi-VSL. It calibrates separately the transmit and receive delays in cables, amplifiers, upconverters, and downconverters, and antenna feeds. the obtained results can be applied as corrections to the TWSTFT measurement, when, before and after a measurement session, a calibration session is performed. Preliminary results obtained at NMi-VSL will be shown. Also, if available, the results of a manual version of the system that is planned to be circulated in September 1994 together with a USNO portable station on a calibration trip to European TWSTFT earth staions.

1. Introduction

The Two-Way Satellite Time and Frequency Transfer (TWSTFT) method (Fig. 1) is used to compare two clocks or time scales which are often located at great distances from each other. The time scale events, normally the 1 pulse per second (1pps) signals, are simultaneously transmitted to the other clock by means of a transmission link through a satellite, normally a geostationary communication satellite. The delays in troposphere, ionosphere, satellite transponder and earth station equipment cancel in first order, the Sagnac correction can be calculated. The biggest source of asymmetry error is the sum of the transmit and receive equipment delay differences of the earth stations involved. For absolute time scale difference determination this sum has to be calibrated to the required uncertainty.

One method to accomplish this is to co-locate the two earth stations and do TWSTFT using a common clock.

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If this is not feasible, a third earth station is subsequent co–located with both stations, and the relative delay difference of each of the two stations is calculated.

A third method is the separate measurement (calibration) at each earth station of the absolute transmit delay and the receive delay by using a special modified translator or Satellite Simulator in front of the antenna and some additional equipment. The required sum of the differences can then be calculated. This method was first described by De Jong (1989).

This paper addresses further progress. The method is developed by simplifying and enhancing the Simulator, a transportable equipment set has been constructed and finally an automated calibration method has been developed and realized.

2. Calibration principle with satellite simulator.

2.1 Single frequency down converting satellite simulator

The transmit frequency F_{up} of a earth station to a communication satellite (Fig. 2) for Ku–band is typical 14 GHz, the receive frequency F_{dn} is lower by a fixed amount, the translation frequency DF. This DF is for e.g. Intelsat in the USA 2295 MHz, in Europe 1495 MHz.

A double balanced mixer suitable for these frequency bands can be used for down conversion by feeding the translation frequency DF into the IF–port (Fig. 3a). When the transmit signal is fed into the RF–port then the LO–port contains the frequency difference (F_{up} - DF), which is the receive frequency F_{dn}. The required power level for DF at the IF–port is 3 to 7 dBm. The conversion loss between the input signal at the RF–port and the output signal at the LO–port is normally less than 10 dB.

An antenna connected to the RF–port receives the transmitted signal in one polarisation and a similar antenna, but with orthogonal polarisation, at the LO–port sends the down converted signal back to the main antenna as receive signal. So this device simulates to what a satellite transponder does, but now the distance to the antenna is short and known.

When performing TWSTFT using this Satellite Simulator, in this case receiving the own signal back (ranging) (Fig. 4), the round–trip delay is measured from modem through cables, the up–converter, the power amplifier, the antenna feed, the distance to the satellite simulator (twice), the internal delay of the simulator, and the complete receive equipment path. The continued measurement of this sum delay already gives an impression of the instability of the equipment, but what we need is the difference between transmit and receive chain. The next chapter is a further step towards this.

2.2 Calibration with a dual frequency dual mixer simulator.

The translation frequency DF can be obtained from a second mixer providing DF as the sum frequency of two other frequencies (Fig. 3b). For a reason we will see later, one of these frequencies is chosen to be equal to the 70 MHz IF frequency of the used modem. So the second frequency should be (DF-70) MHz. However, the output level of the second mixer is too low to excite the first mixer, and a wide band amplifier needs power, is active, and has a delay to be measured. A solution is to place the RF and LO ports of the two mixers, as two down convertors, in series (Fig. 3c).

This works similar to the circuit (Fig. 4) of paragraph 2.1 (see Fig. 5): the transmitted signal is received back from the simulator, provided that 70 MHz and (DF-70) MHz signals of >3 dBm are fed into the IF–ports of the two mixers. The sum DLY1 of the transmit and receive delays TT(k)+TR(k) can be measured.

The 70 MHz Continuous Wave (CW) signal and the 70 MHz Transmit PN modulated signal from the modem are then interchanged (Fig. 6). The 70 MHz CW signal is up–converted to the transmit frequency F_{up}. The input to the mixers has become a unmodulated CW signal of e.g. 14 GHz. But the down conversion now uses a 70 MHz PN modulated signal, so the output signal from the satellite simulator is a PN modulated signal as before. Now the sum (DLY2) of the 70 MHz Reference Cable from modem TX output to the 70 MHz input of the simulator and the receive chain delay TR(k) is measured.

By using two other cables the delay of the used 70 MHz Reference Cable (DLY3) can be calibrated. Subtraction of DLY3 from DLY2 gives the receive delay TR(k). Subtraction of TR(k) from DLY1 gives the transmit delay TT(k). If this procedure is followed at both earth stations, and the values exchanged, the needed sum of transmit and receive delay differences can be calculated; the internal modem transmit delay should also be measured using a digital oscilloscope or the method described by De Jong (1989) and the resulting internal delay difference should be incorporated in TT(k) and TR(k).

3. Improvement: dual frequency single mixer simulator

The simulator with two mixers in series works well. However, there are some disadvantages. Firstly the asymmetry: the mixer with the 70 MHz port is closer to one of the antennas, giving a small delay difference. Secondly, the 70 MHz signal is connected directly to the mixer IF–port which can give mismatch and consequently signal reflections leading to a "multi–path" effect. Thirdly the total conversion loss is doubled: 15 – 20 dB. Realizing that a mixer has its properties due to its non–linear characteristic, it was realized that a linear addition of two signals fed into a non–linear device should produce spectral components at the sum frequency as well as the difference frequency.

For addition of the 70 MHz and the (DF-70) MHz signals we have used a wide band (DC–12 GHz) resistive power combiner PD (Fig. 7). This device has 3 ports with equal properties and delay to the other ports. One disadvantage is the 6 dB insertion loss but the mismatch of the mixer IF–port to the cable is also reduced by this decoupling. Good results were obtained. The 70 MHz signal level for both the CW and the PN modulated signal should be at least at +8 dBm before the power combiner. An amplifier is added in the 70 MHz CW path for this purpose.

3.2 Construction of the Satellite Simulator

The resistive power combiner is placed in the satellite simulator box together with the mixer and the two antennas (Fig. 8). As inexpensive antennas we use two wave guide to coax adapters. They work fine, but might give some reflection back to the antenna dish.

The plastic material of the box is transparent to the frequencies concerned, so no hole was needed for the antennas. A nice symmetric component lay–out was adopted. Interconnections have been made (thanks to Mr. A. Trarbach, NMi Electronics Lab!) with semi–rigid coaxial cable and SMA connectors. The internal delay from antenna to antenna is 2 ns and matches the delay from the 70 MHz input to both antennas within 0.1 ns.

4. Portable Satellite Simulator Calibration equipment.

Two Satellite Simulators were built accordingly. One was placed in front of our fixed TWSTFT earth station. The other was used to assemble a portable earth station delay calibrator. This was used at several stations during the European TWSTFT Calibration Trip with the USNO movable earth station (FAST) in September and October 1994; it was also used to calibrate the FAST delays. The equipment was completed with two boxes (see Fig. 5), one containing a 5 MHz distribution amplifier and a 70 MHz source, both derived from the 5 or 10 MHz reference at the station and the other containing the 70 MHz amplifier and a source for (DF-70) MHz, which is 1425 MHz for Europe. This frequency was also phase locked to the 5 MHz reference at the stations. It is tunable in 5 MHz steps. When using the same translation frequency as in the satellite, the signal from the satellite is also present during calibration. To avoid possible interference, the antenna pointing should be changed to avoid pointing to the satellite or the source should be tuned to a slightly different translation frequency. Most stations have mechanical adjustment for azimuth and elevation, therefore the source was tuned to 1430 MHz. The receive frequency for the calibration was now 5 MHz lower than for the satellite. This is expected not to give a significant delay difference. Also a set of cables, up to 100 m length was included as well as the power supplies. The total mass was about 30 kg.

5. Automation of the Calibration

From TWSTFT experiments it is seen that at integration times greater than 200–300 s the Allan Deviation indicates an increase in instability. One of the reasons can be the change of the delays in the station equipment. Only if the delays in the transmit and in the receive equipment changes by the same amount at the same time, they cancel and do not influence the instability. The proposed method with the Satellite Simulator measures the TX and RX delays separately. So this method can be used for investigation of the delay changes but also to measure and then correct the data for possible changes. In the latter case the long term frequency transfer capability of TWSTFT would also improve. To do this, the calibration has to be automated.

NMi VSL has developed a automated measurement system for all equipment and cables. However, with exception of the internal 70 MHz TX and RX modem delays; this modem is in a temperature and humidity controlled room and are expected to have the least change.

5.1 Design considerations

The automation should not disturb the correct termination of cables. When a cable carrying a signal temporary is not used, it is to be terminated correctly. A solution for this is the use of so–called transfer switches: when a switch is activated the existing path is changed and a second path is substituted (Fig. 9). These switches are available in the form of coil–activated coaxial switches, relays. These relays are activated from a IEEE–488 bus through a relay adapter.

Our MITREX 2500 was already made programmable through such a device, and the same applies to the setting of the transmit frequency and the receive frequency. The calibration of the total delay of the 70 MHz reference path (the 70 MHz CW cable, the amplifier, and even the 70 MHz cable to the Satellite Simulator) is also included (Fig. 10).

5.2 Description of the measurements (Fig. 10).

5.2.1. Measurement of the sum of internal TX and RX modem delays.

Switch the modem into the TESTLOOP Mode. Now the TX output and the RX input of the modem are interconnected internally. The average Time Interval Counter (TIC) reading is stored as [1].

5.2.2 Measurement of the 70 MHz Reference path.

5.2.2.1 Determination of sum of the delay of the 70 MHz TX and the 70 MHz RX cable.

Only the switches A and B are activated. Two ports of the power combiner PC are used to interconnect the far ends of the TX and RX cables, the third port is terminated in a termination T. The TIC reading is averaged and stored as [4].

subsubsubsect5.2.2.2 Determination of sum of the delay of the 70 MHz CW + amplifier and the 70 MHz TX cable.

Only switches 1, 2, 3, C and A are activated. Two ports of the Power Combiner (PC) are used to interconnect the far ends of the CW and RX cables, the third port is terminated in a termination T. The TIC reading is stored as [5].

5.2.2.3 Determination of sum of the delay of the 70 MHz CW + amplifier and the 70 MHz RX cable.

Only the switches 1, 3, C and B are activated. Two ports of the power combiner PC are used to interconnect the far ends of the CW and RX cables, the third port being terminated in a termination T. The TIC reading is stored as [6].

5.2.2.4 Determination of sum of the delay of the 70 MHz CW + amplifier, the two cables to the Satellite Simulator and the 70 MHz RX cable.

Only the switches 1, D and B are activated. Two ports of the power combiner PC are used to interconnect the far end of the CW cable, the two Satellite Simulator cables and RX cables, the third port is terminated in a termination T. The two cables to the Satellite Simulator are interconnected by a power combiner in the Satellite Simulator. The TIC reading is stored as [7].

5.2.2.5 Calculation of the 70 MHz Reference path delay.

The delay of the 70 MHz CW cable + amplifier is: 0.5([5] - [1]) + ([6] - [1]) - ([4] - [1]) [8] The delay of the sum of the two cables to the Satellite Simulator is [7] - [6]; because of the fact that the two cables are co-located and of the same type the delay of one cable is calculated by the ratio R of the length of that cable compared to the sum of the lengths of both cables. In our case both cables have the same length, so R= 0.5, thus the delay [9] of one cable is: 0.5([7] - [6]).

The total 70 MHz Reference path [10] is now: [8] + [9]

5.2.2. Measurement of the sum of all TX and RX delays.

For this measurement all relays remain in the inactive position. However, the receive frequency is lowered by 5 MHz to receive the signal from the Simulator in stead of the signal from the satellite (otherwise the antenna should be pointed away from any satellite). The reading of the TIC is averaged and stored as [2].

5.2.3. Measurement of the sum of 70 MHz reference cable and the RX delays.

Now only switch 1 is activated, so the 70 MHz CW and the 70 MHz TX signals are interchanged. The average TIC reading is registered as [3].

5.2.4 Calculation of the TX and RX delays.

The RX delay is: ([3] - [1]) - [10] [11] The TX delay is: ([2] - [1]) - [11] [12]

5.3 Wiring Delays

In the calculations in 4.2 the small and constant delays in the relays, power combiners and associated sort wirings were not mentioned, but these small delays of up to 1 ns were measured and are used as correction constants in the software. It appears that the length of a signal path through a high frequency device mostly is a good measure for its delay, the same as for coaxial cable: 5 ps for 1 millimeter.

6. Advantages of incorporation of Calibration sessions in regular TWSTFT measurements.

The Calibration measurements as described in 4.2 can be performed in a calibration session. Such a session can precede and follow a TWSTFT session. From the delay change, a rate of change can be determined and the results from the TWSTFT sessions can then be corrected for that change.

Changes in cables and equipment are also detected and can be corrected for. Corrections could be done also during a long period; when both of a pair of TWSTFT stations do this, then also the frequency transfer instability of the TWSTFT between them is improved because of a lower flicker floor. The remaining instrumentation instability source will then be restricted to the instability of the modems and the counters, apart from the reference clocks themselves.

7. Status and some results at NMi–VSL

Part of the system was installed and used since July 1994; the Relay system is now also installed (nov. '94), except the connections of the relays to the relay interface. Changes to our software will then be performed to incorporate the fully automated calibration in a Calibration session.

Fig. 11 shows the behaviour over about 4 months of our modem when TESTLOOP measurements are done. Fig. 12 shows results over the same period of Satellite Simulator loop (TX + RX delay) measurements. Results for the automated calibration system will become available next year. Also results from calibrations with the portable delay calibrator compared to the FAST calibration will be reported later.

8. Conclusion

The feasibility of this fully automated delay calibration system for a TWSTFT earth station using a special modified Satellite Simulator has been shown. It clearly detects and measures delay changes in the TX and RX path separately. It is a suitable and cost–effective tool to improve the instability of frequency and time transfer by means of the TWSTFT method.

9. References

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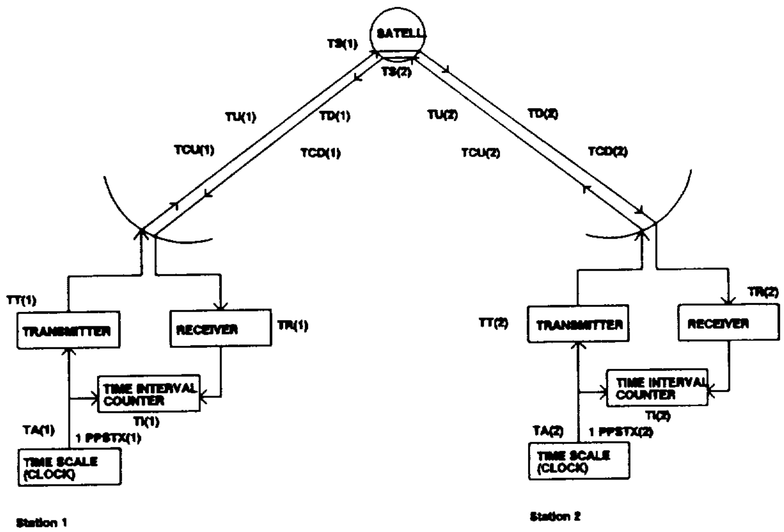
- Davis, J A and Pearce, P R 1993, *"Characterization of the signal delays in a ground station designed for satellite two way time transfer"*, Proc. EFTF 93, Neuchatel, pp. 113–118.



The timescale difference is given by:

TA(1) - TA(2) =	+0.5{TI(1)}	(TIC reading at 1)
	-0.5{TI(2)}	(TIC reading at 2)
	+0.5{TS(1) - TS(2)}	(Satellite delay difference)
	+0.5{TU(1) - TD(1)}	(Up/down difference at 1)
	-0.5{TU(2) - TD(2)}	(Up/down difference at 2)
	+0.5{TT(1) - TR(1)}	(TX/RX difference at 1)
	-0.5{TT(2) - TR(2)}	(TX/RX difference at 2)
	-0.5{TCD(1) - TCU(1)}	(Sagnac + sat. movement)
	+0.5{TCD(2) - TCU(2)}	(Sagnac + sat. movement)

Figure 1. Two-Way Satellite Time and Frequency Transfer Method

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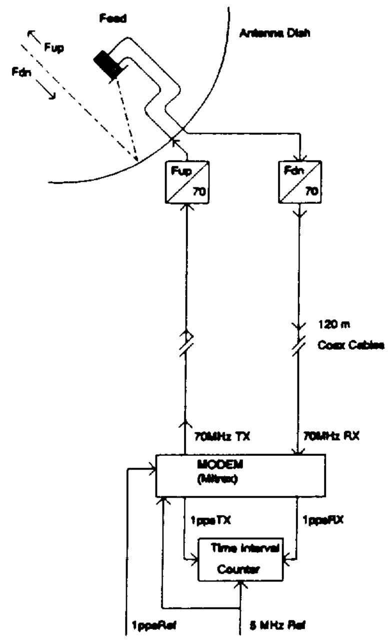

Figure 2. Typical TWSTFT Earth Station Configurat

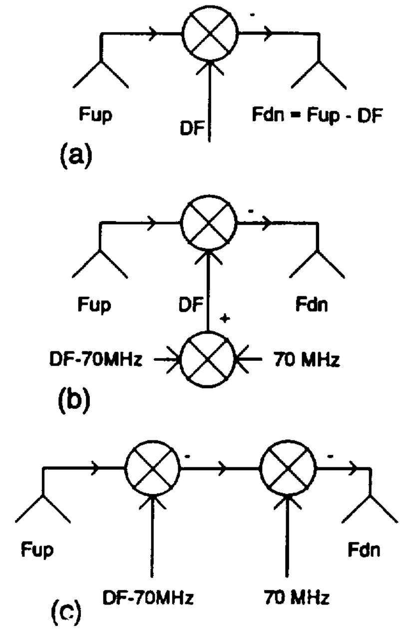

Figure 3. Different Translator Mixer Schemes

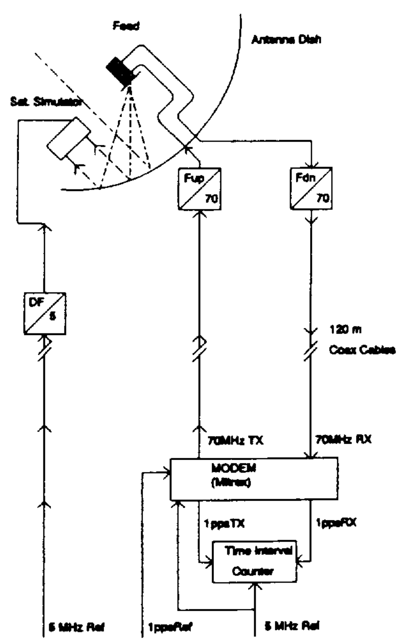

Figure 4. Ranging Using a Satellite Simulator

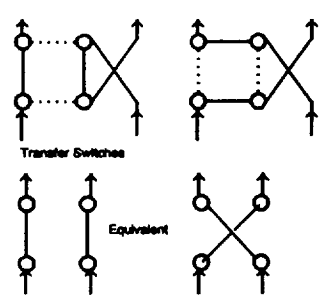

Figure 9. Transfer Switches

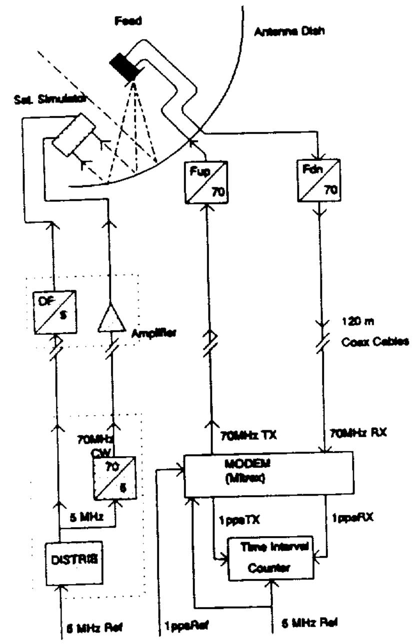

Figure 5. (Portable) Satellite Simulator for Measuring TR(k) + TT(k)

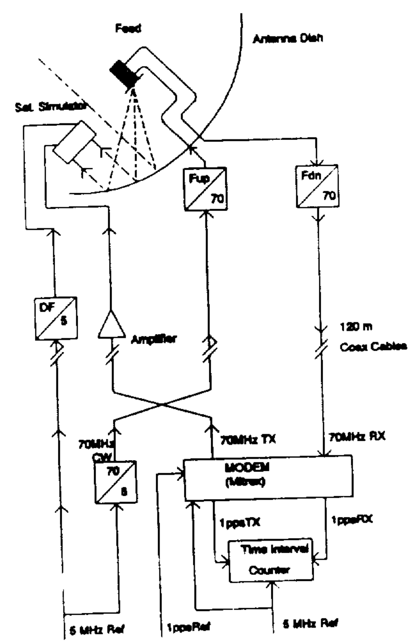

Figure 6. Satellite Simulator for Measuring TR(k) + Reference Path

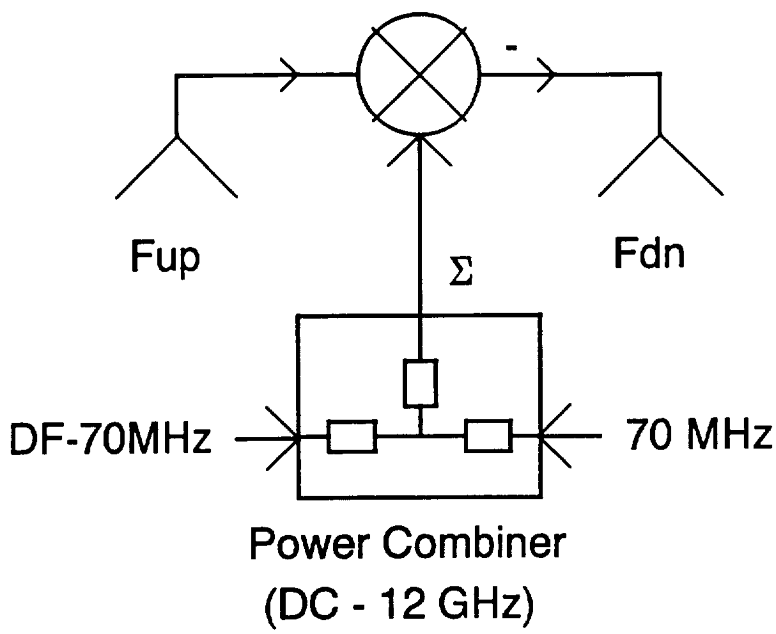

Figure 7. Use of Power Combiner and One Mixer

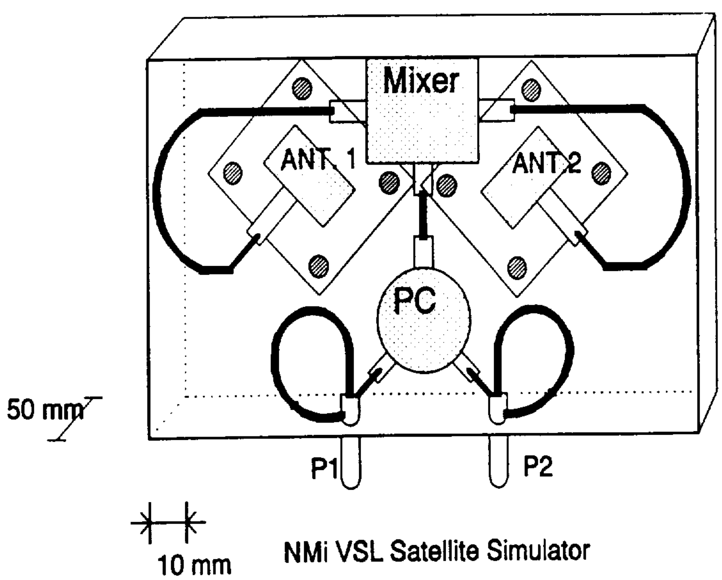

Figure 8. Layout of the NMi Satellite Simulator

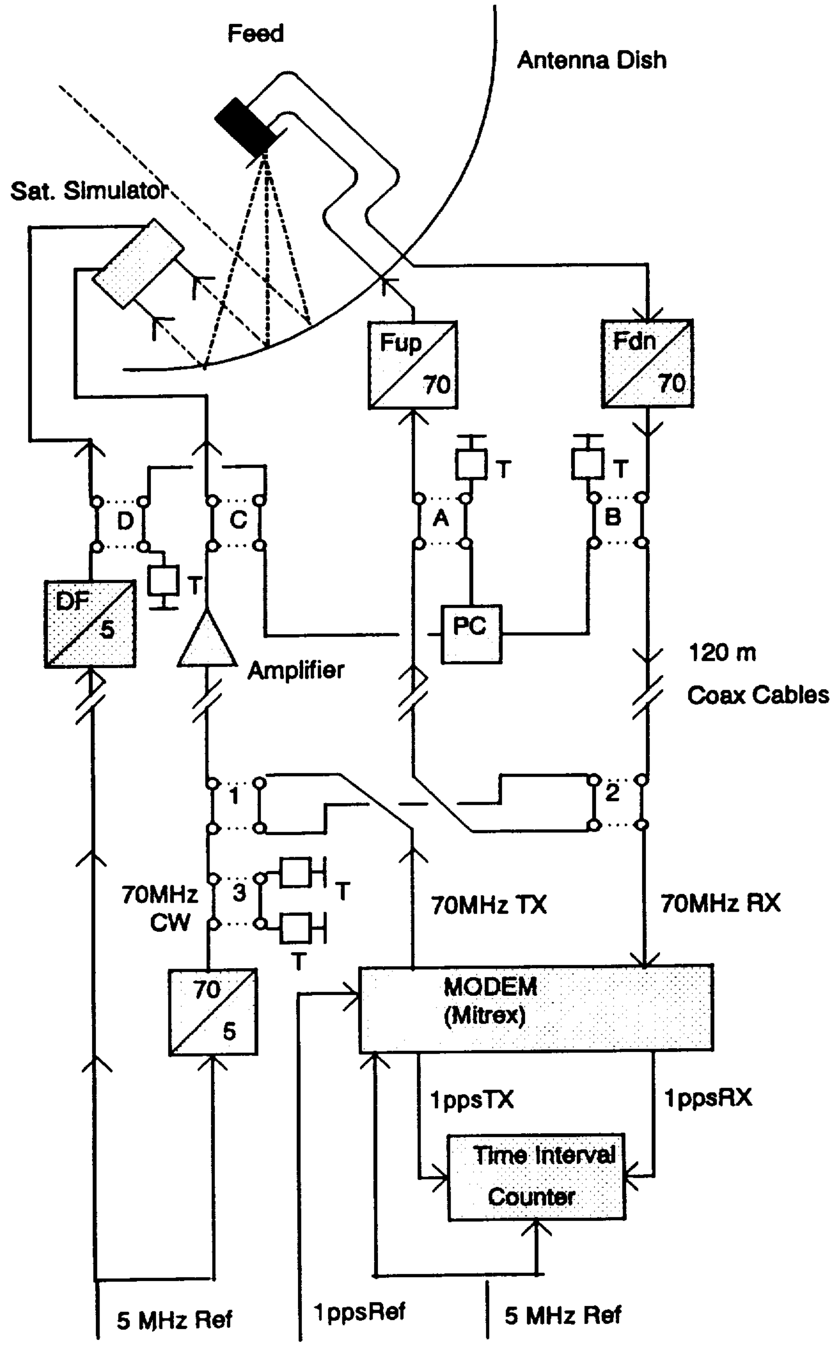

Figure 10. Automatic Delay Calibration System for TWSTFT Stations

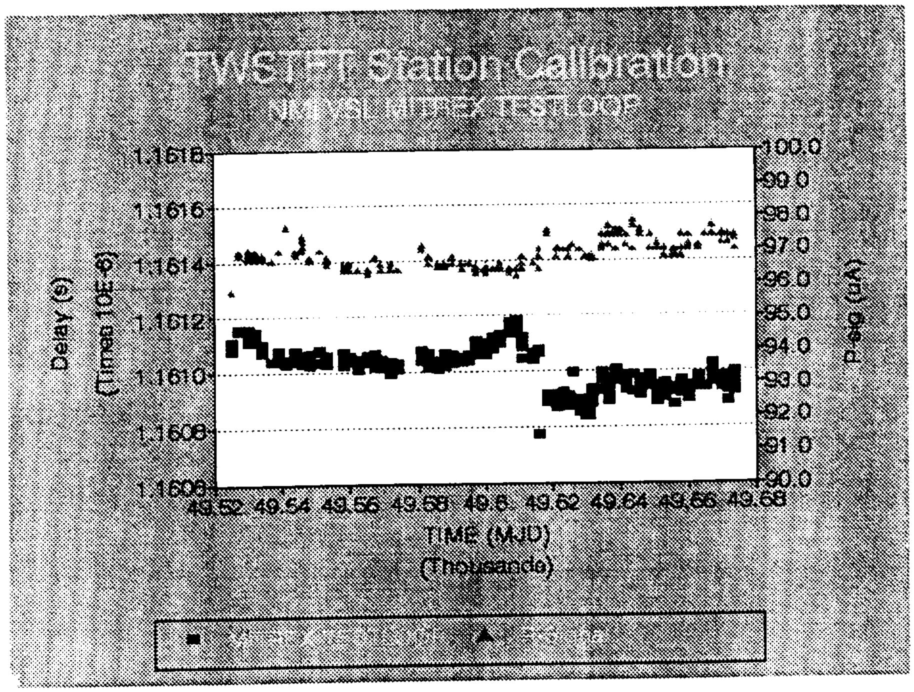

Figure 11. VSL MITREX Modem TESTLOOP Delay July - November 1994

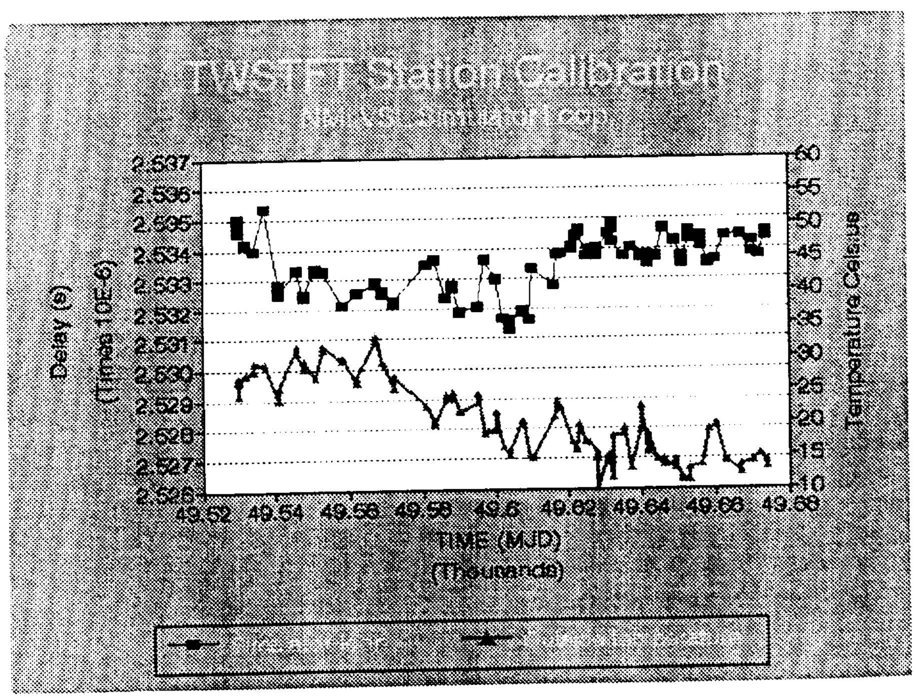

Figure 12. VSL RX+TX Delay July - November 1994

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